High Gradient RF Studies

J. Norem

Argonne

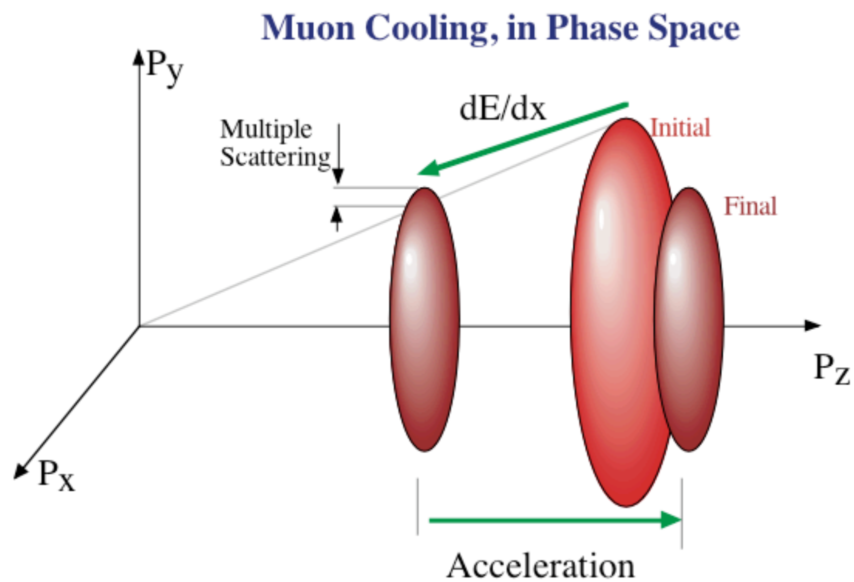
SMTF Workshop

Fermilab

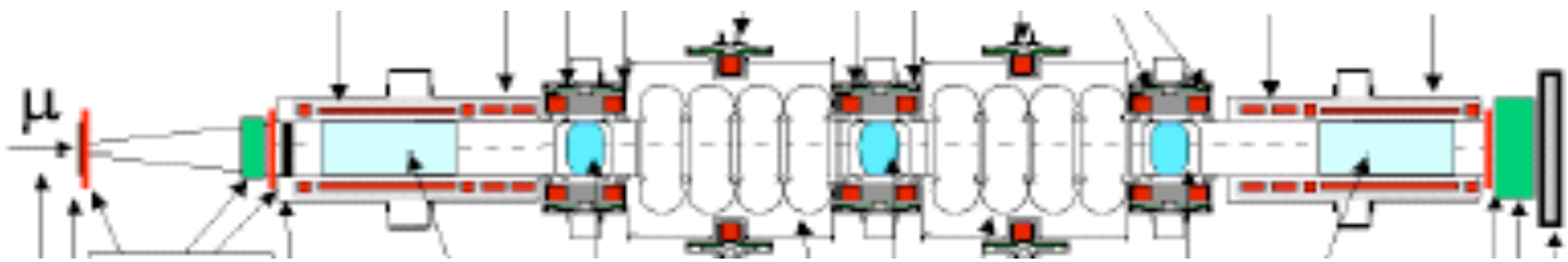
Oct. 4, '05

Our work is directed at Muon Collaboration problems.

- Cooling muons requires absorbers and rf.



- X rays make backgrounds in the Muon Ionization Cooling Experiment (MICE)



scattering measuring acceleration+absorbers=cooling measuring

- Goals: 1) Insure we can reach full E field with 3 - 5 T solenoid.
  2) Reduce backgrounds in spectrometers.

Collaborators

- Experiments in Fermilab Muon Test Area (MTA)
  - J. Norem, Argonne
  - A. Moretti, A. Bross, Z. Qian FNAL
  - Y. Torun, IIT
  - D. Li, M. Zisman, LBL
  - R. Rimmer, JLab
  - R. Sandstrom, Geneva University
- Modeling
  - Z. Insepov, A. Hassanein, I. Konkashbaev, ANL
- Surface studies
  - D. Seidman, J. Sebastian, K. Yoon NW
  - P. Bauer, C. Boffo, FNAL

We have a program directed at understanding rf limits.

This was started to understand muon cooling problems.

- There are three coordinated efforts:
    1) Low frequency cavity studies (Muon Collabration)
    2) Atom Probe Tomography (ILC and Muon Collaboration)
    3) Modeling (generally applicable)

- We are converging on a general theory of vacuum breakdown.

- We are producing unique data on high gradient environments.

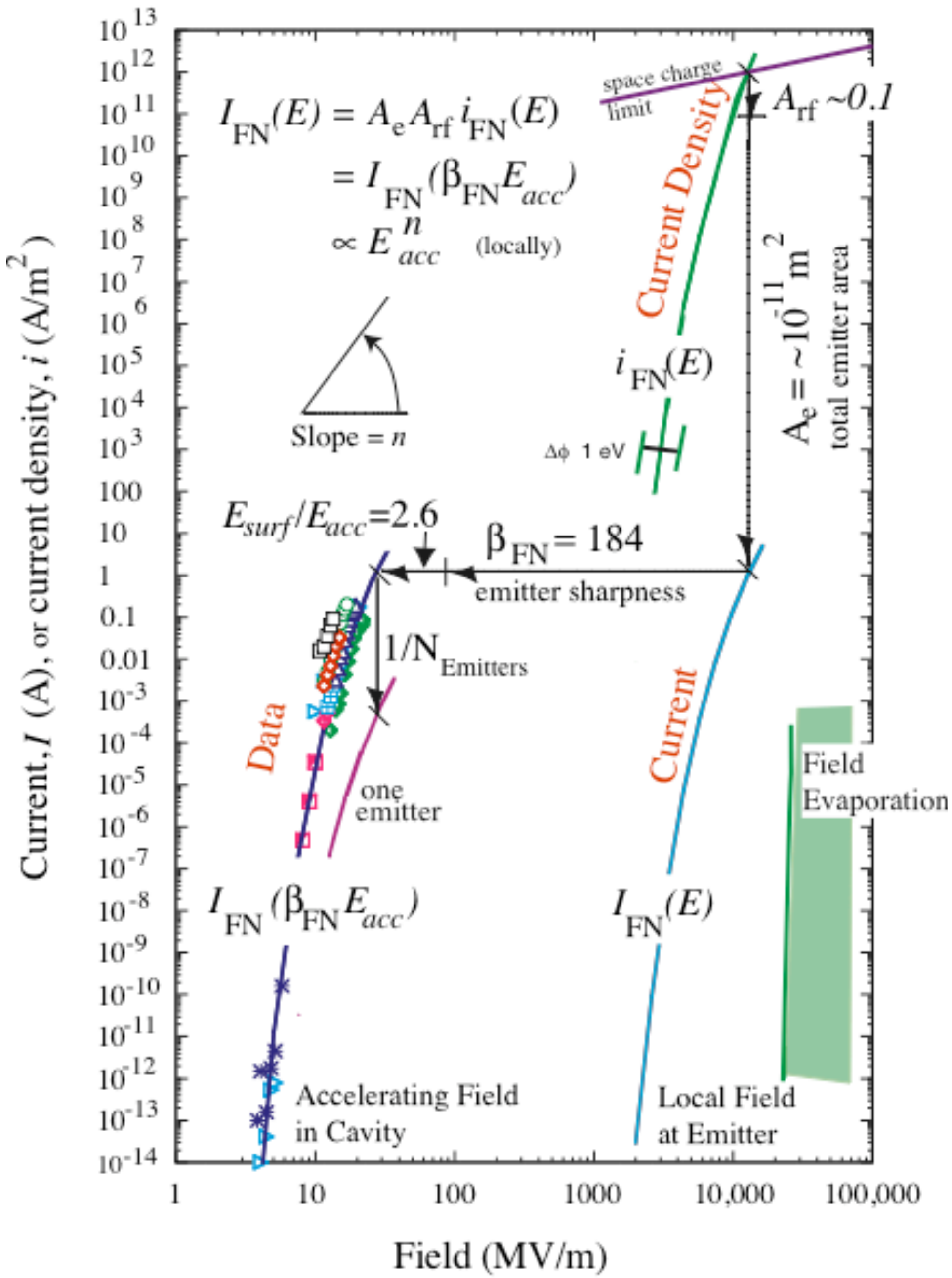
- Our work should be relevant to ILC/SCRF, CLIC, DC . . .

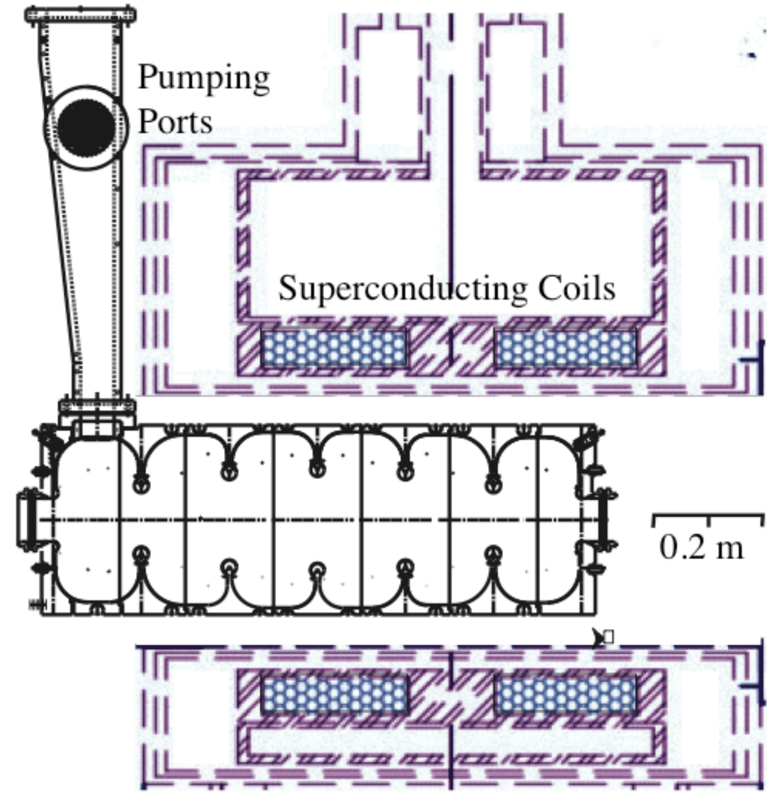
- We argue that **High Gradient Studies is one field**.

    Superconducting rf,
    Normal Conducting rf
    DC vacuum breakdown

    } are limited by same mechanisms,
    . . at the same value of *E*.

Data at Fermilab measured the local environment at emitters.

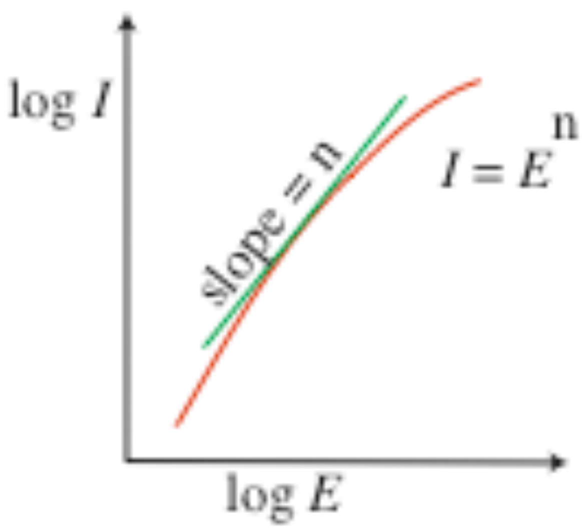




Emitter dimensions ~ 0.1 μ
Surface field ~ 10 GV/m

Measuring local electric fields is straightforward.

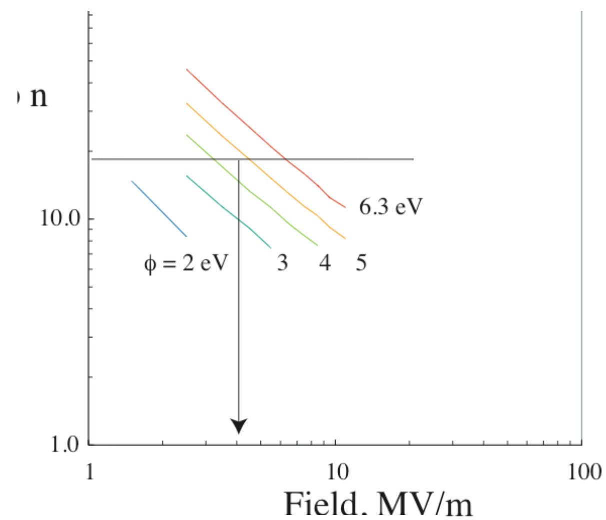
- The slope of the curve $\log_{10} I$ vs. $\log_{10} E$ gives the exponent of $I \sim E^n$.

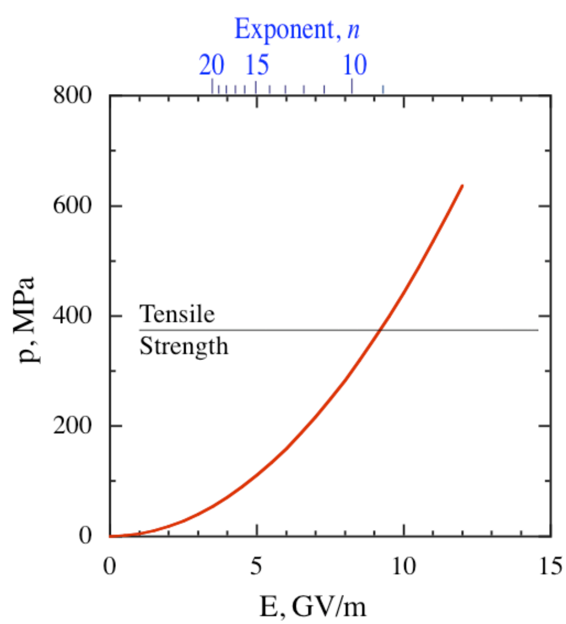


- Stresses are determined by E_{local},

$$\sigma = -0.5\, \varepsilon_0 E^2.$$

- The value of n and ϕ, the work function, determine the local field.





Our Breakdown Model

- Electric fields produce tensile stresses that fracture the surface.

Local fields with E > 6 GV/m damage surfaces.

- Dark currents describe asperities with E_{local} ~ 4-10 GV/m, dimensions ~ 0.1 μ.

- At this field the electrostatic tensile stress ~ tensile strength.

  We see damage in normal rf systems

  There seems to be damage in superconducting rf systems

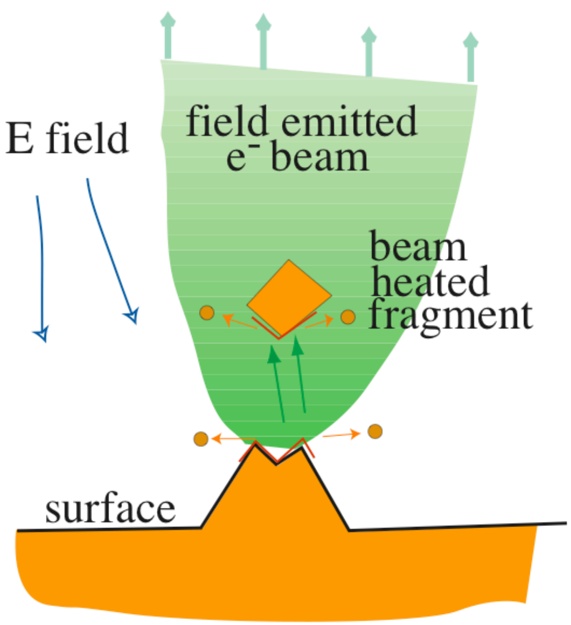
  The atom probe system shows damage

- The damage can trigger breakdown.

  Fragments / clusters are torn off.

  Field emitted beams vaporize fragments

  Lossy plasmas short cavities.

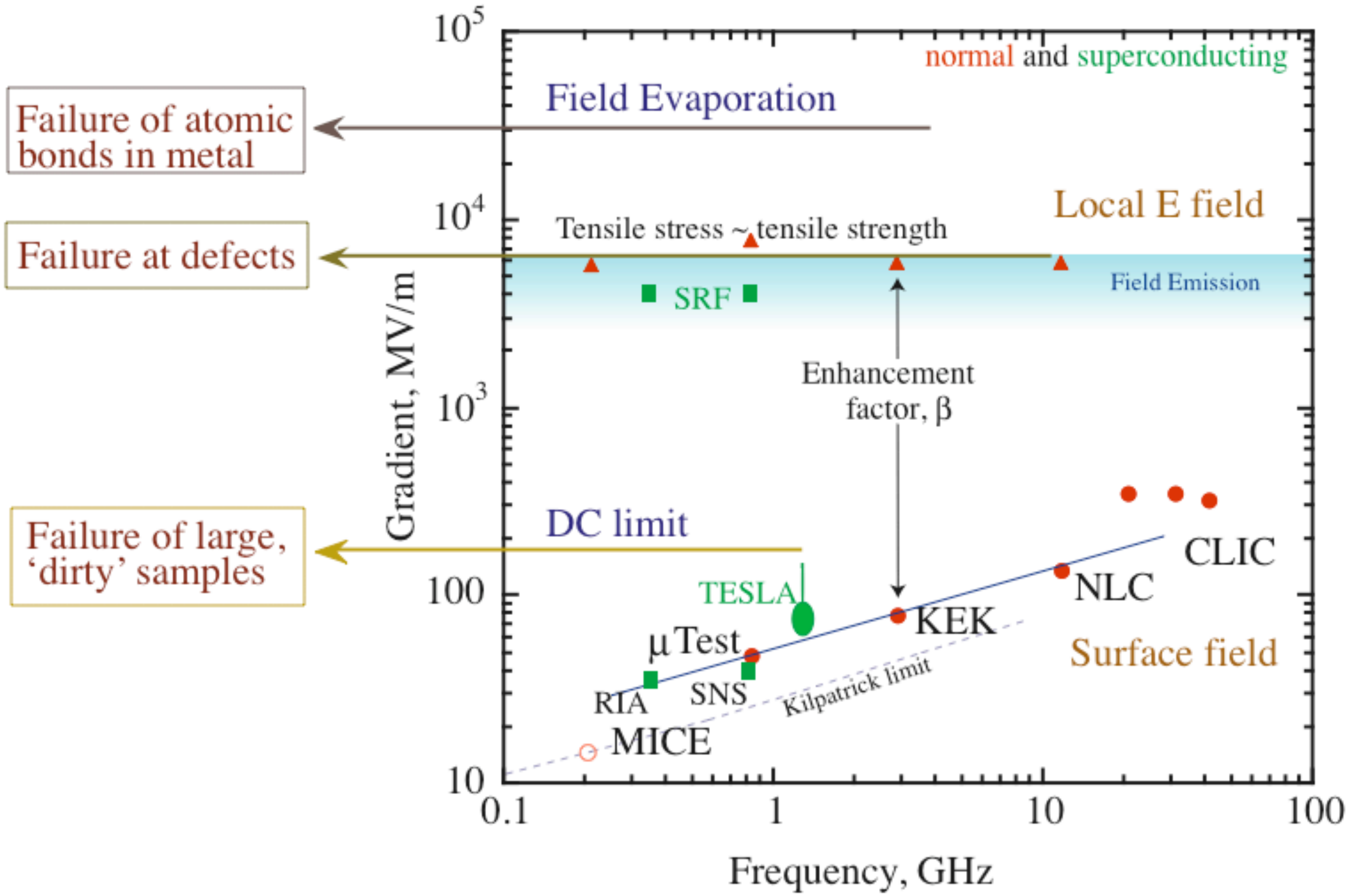


- Details in 3 recent Phys. Rev. STAB papers, a NIM paper, PAC05, EPAC . . .

Our model is consistent with data.

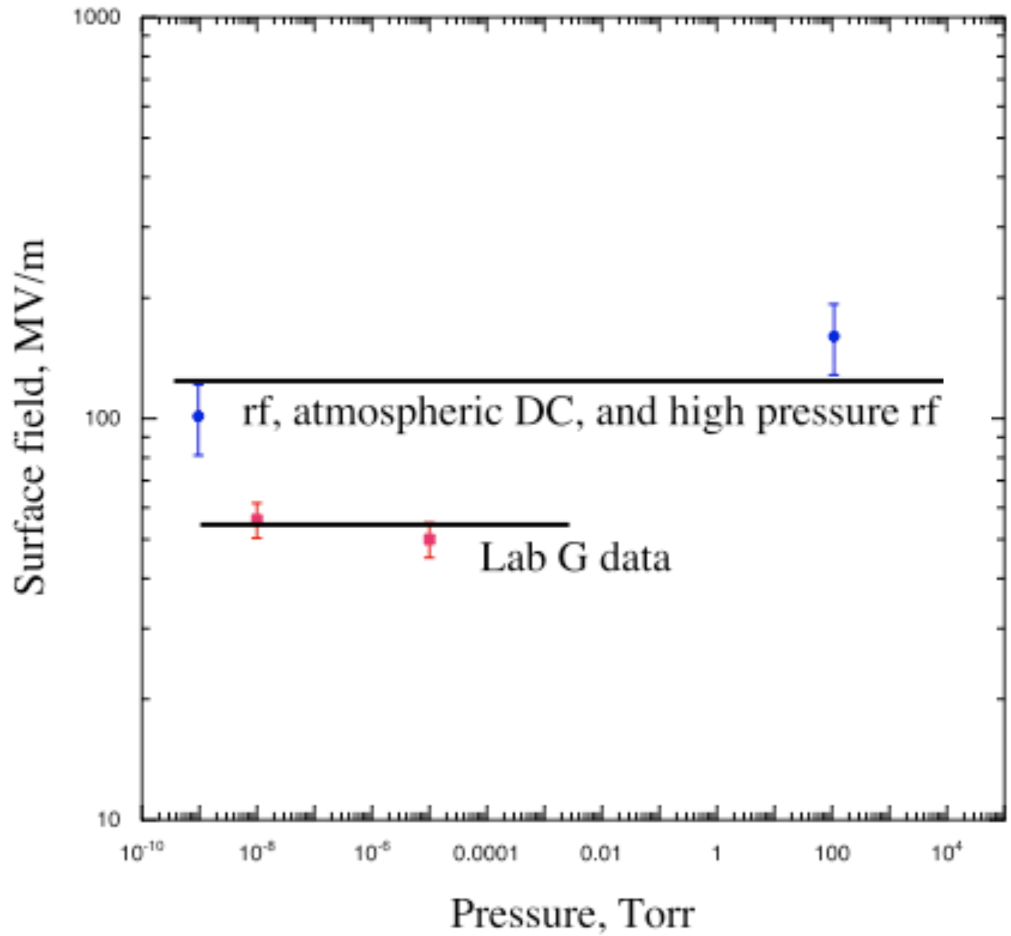
- DC to 30 GHz – breakdown occurs with local fields ~ 7 GV/m.
- Material properties – failure if tensile stress ~ tensile strength is unsurprising.
- Vacuum / gas pressure – little variation from 10^{-11} to 10^{5} Torr.
- Different materials – harder materials better (oxides may matter - not neat).
- Temperature dependence – weak dependence is predicted.
- Secondary emitters – may determine operating fields – we have new data
- Breakdown gap – from micron (DC) to meter (rf) scales.
- Strong magnetic fields - torques within emitters seem to dominate.
- Cavity conditioning – breakdown occurs at constant local electric fields.
- Rapid development of spark – determined by high power density of FE e^-.
- Pulse length – fatigue can explain pulse length dependence - no predictive power.
- Atom probe data – at 5 – 10 GV/m, surface layers can belch and pop.
- Superconducting RF – similar mechanisms, gradient limit at E_{local} ~ 5-10 GV/m(?).
- Light and power switching – in the lab, and in the home.

Accelerating gradients are limited by local E fields.



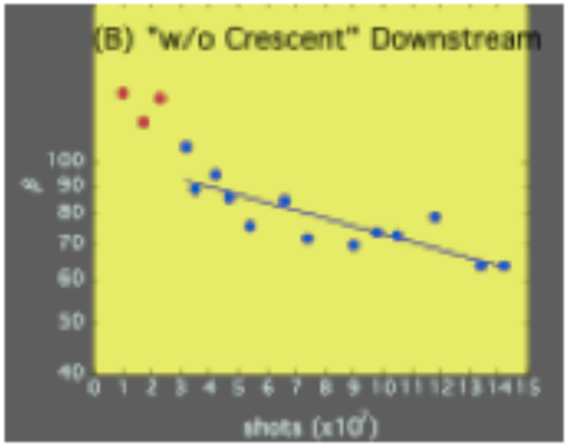
Gas Pressure doesn't seem to matter much.

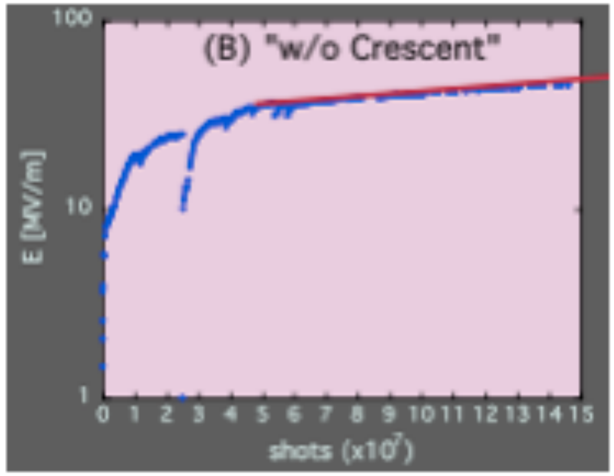
- From 10^{-11} to 10^{2} Torr, breakdown fields are pretty constant - if the configuration is set up so that there is no gas avalanche.
- Muons Inc. data extends and confirms these results to even higher pressures.

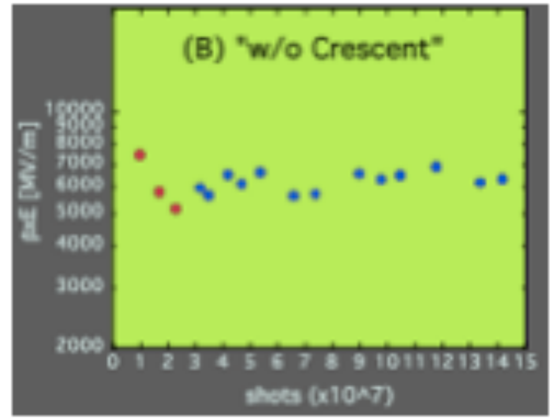


Local fields are constant during conditioning.

Local field constant during conditioning (gradients and enhancements change) - KEK





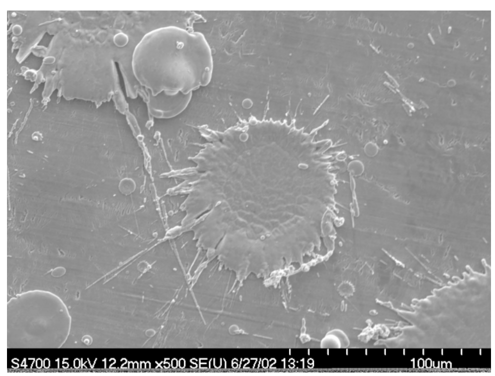


Enhancement factor Surface field = 6 - 7 GV/m

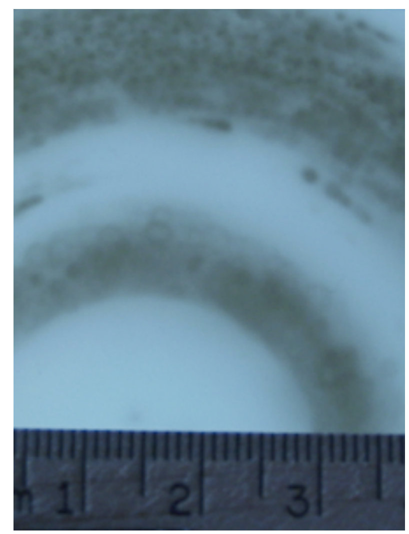
Emitters and electron beams.

- The beams we see are consistent with the surface we had in the cavity.

emitters

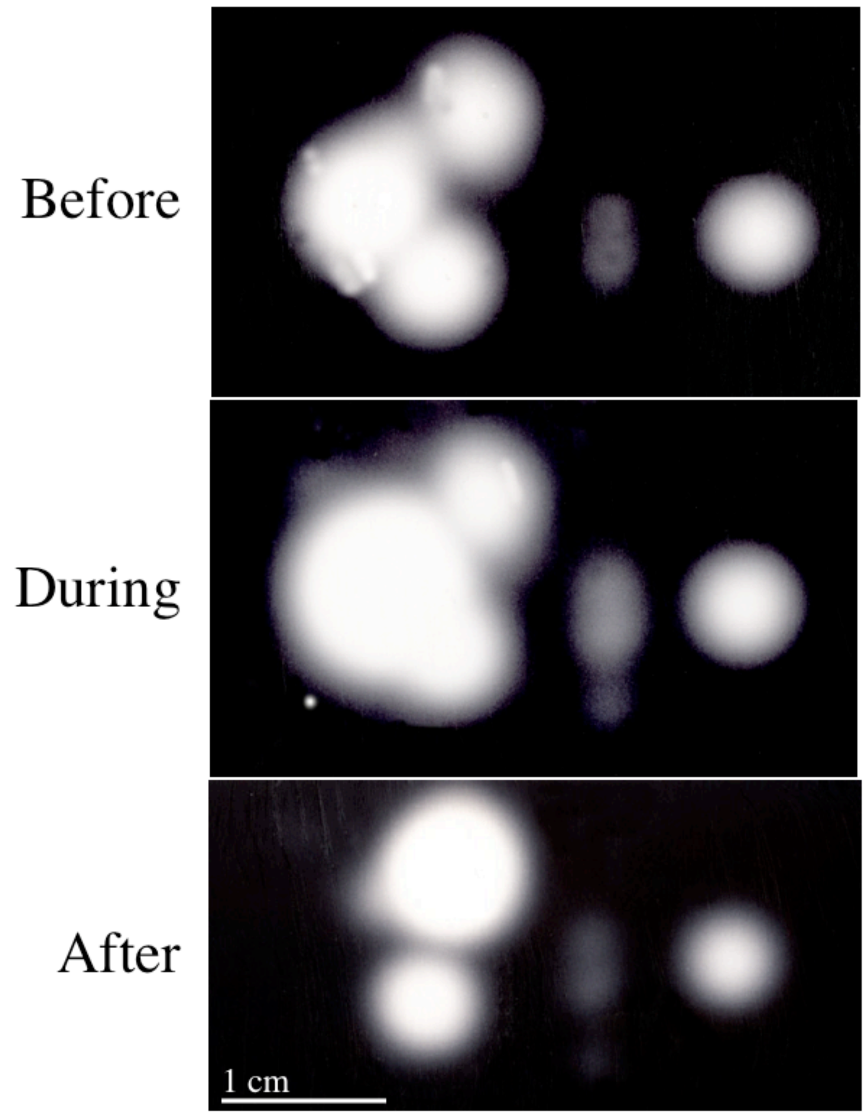


beams



Breakdown events change the pattern of field emitters.

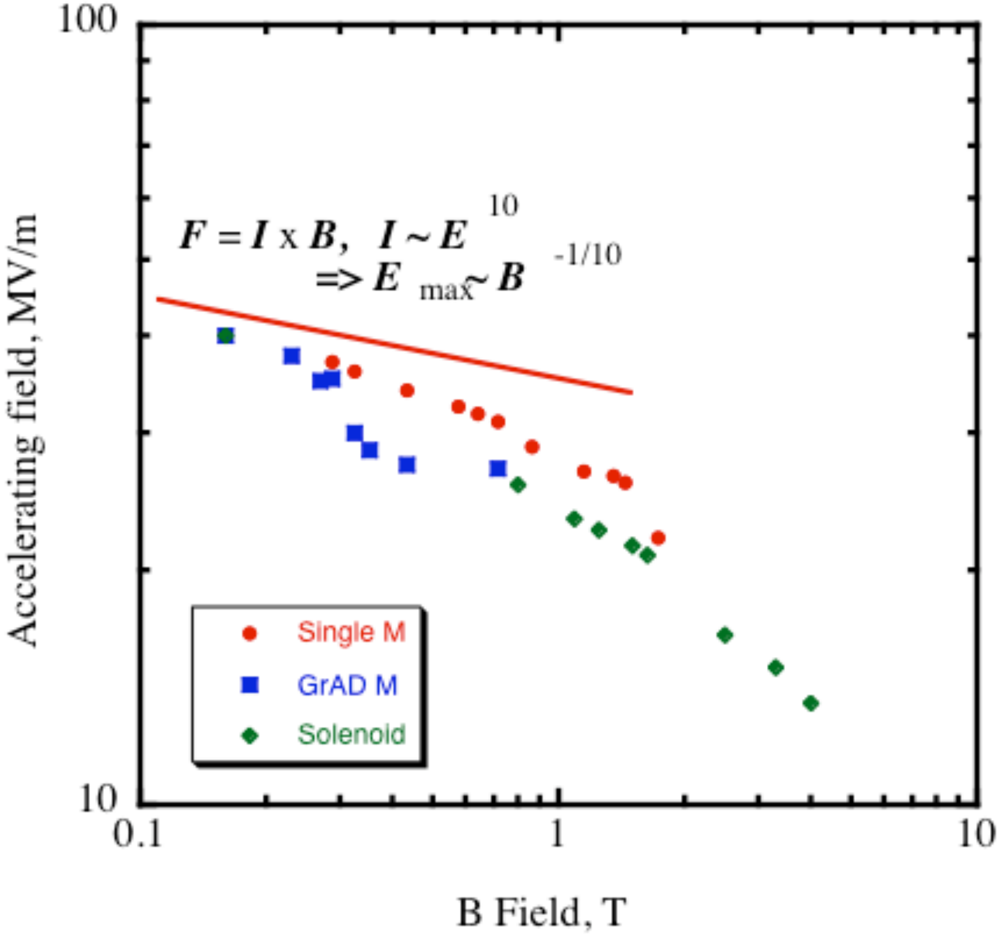
- We look at dark current spots before, during and after an event.
- The brightest emitter disappeared during the event.



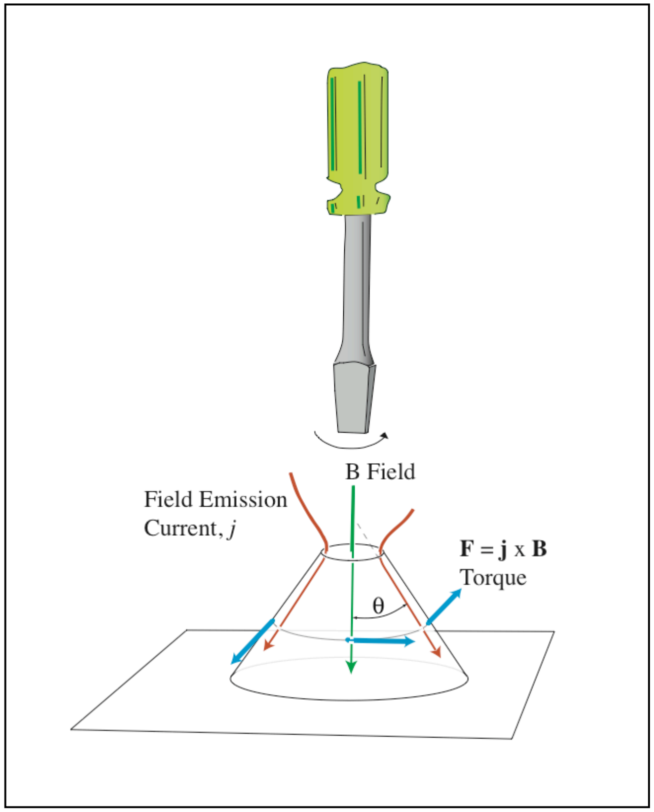
Magnetic field data is consistent with *J* x *B* effects.

- ***j*** x ***B*** forces are driven by field emission currents <u>in</u> the emitter.

The data

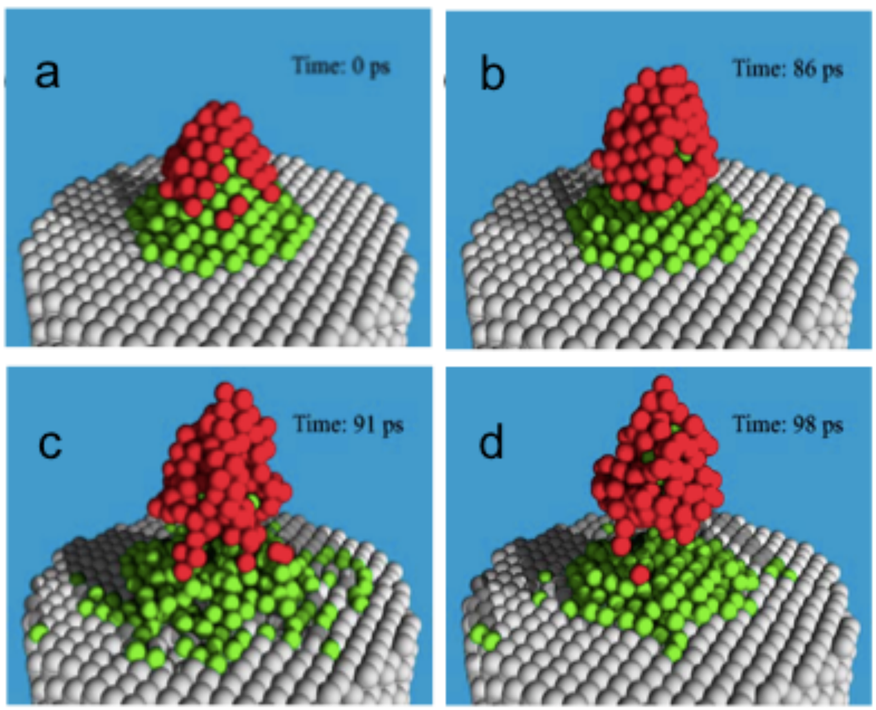


The model



Temperature effects are small.

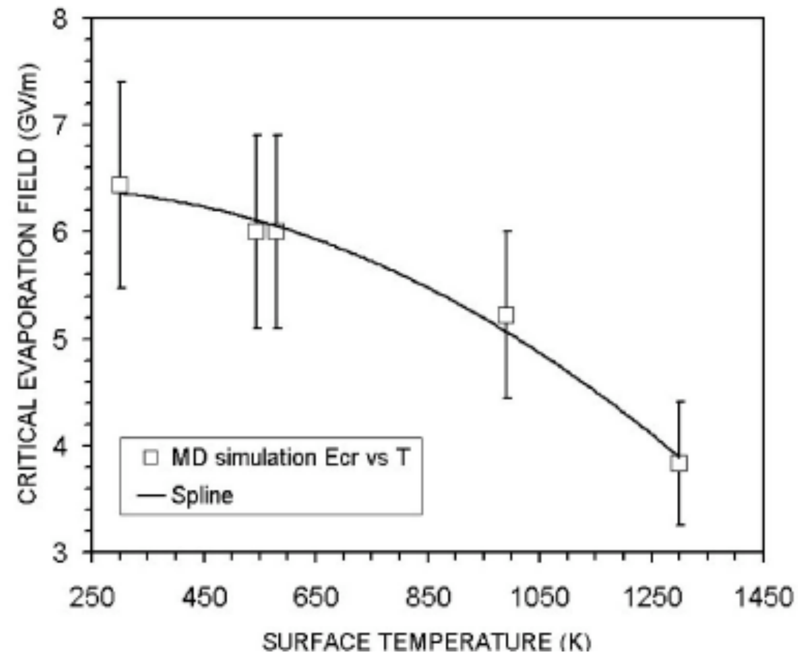
- Zeke Insepov has been modeling cluster emission using his code.



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 7, 122001 (2004)

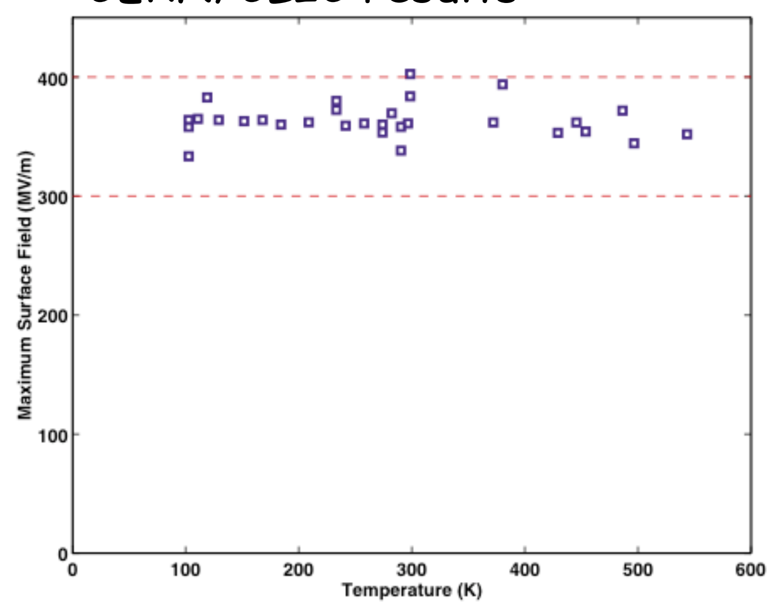
New mechanism of cluster-field evaporation in rf breakdown

Z. Insepov, J. H. Norem, and A. Hassanein
Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439, USA
(Received 26 April 2004; published 22 December 2004)



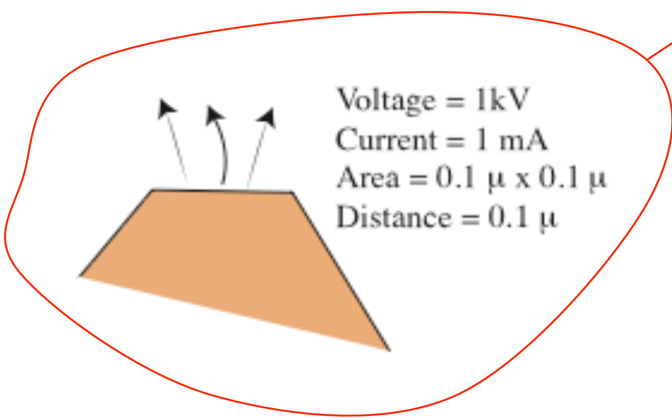
Modeling

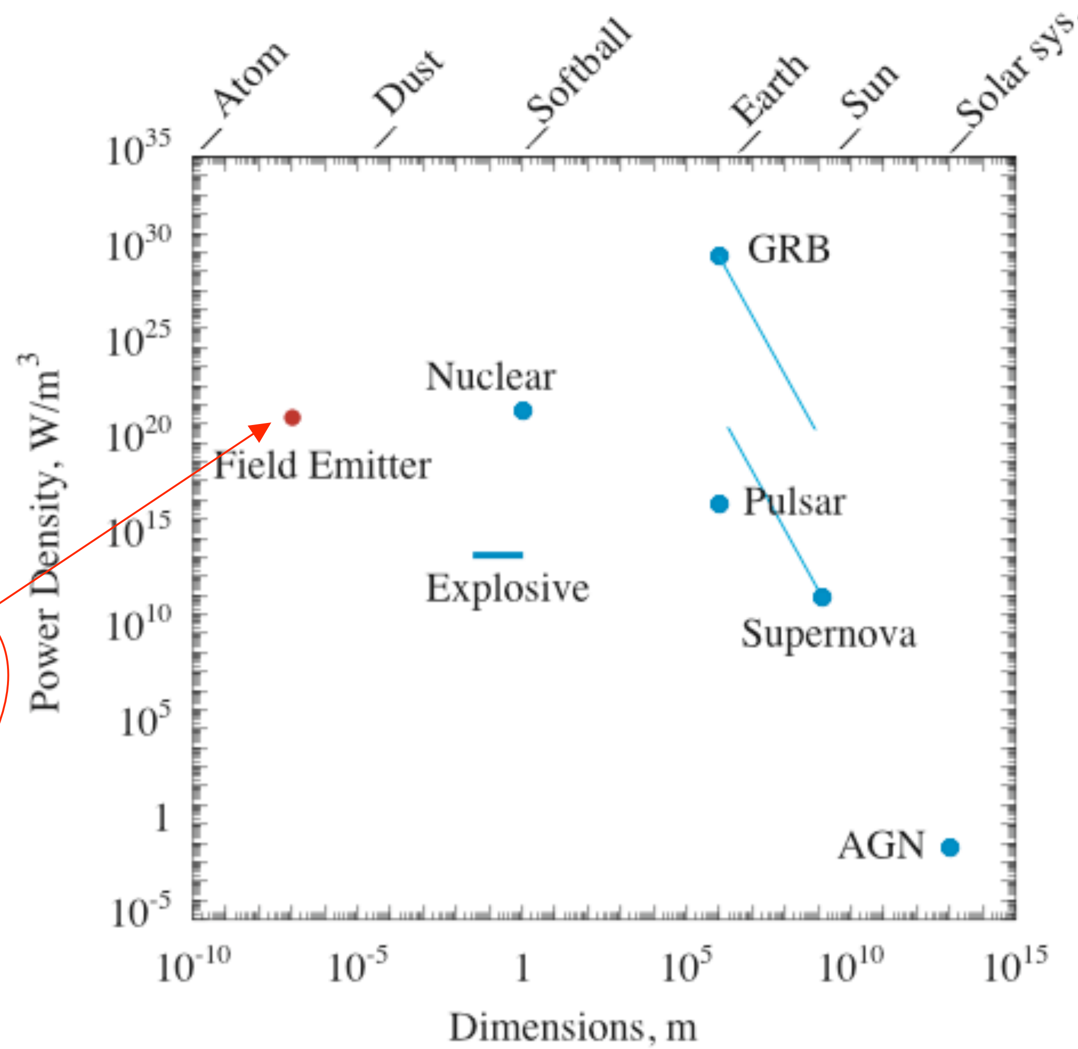
CERN/CLIC results



The highest power density in the universe ? ? ?

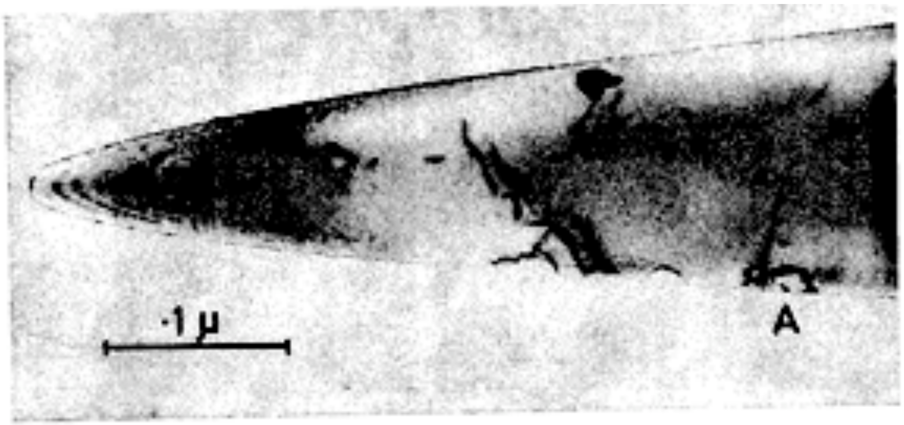
- Highest electric field compatible with macroscopic solids.
- Highest currents compatible with these electric fields
- Higher power density than every other "normal" phenomenon (?)
- How big are GRBs?
  Supernovae?
- In the home?





High fields cause mechanical failures.

- Stresses cause failures in Field Ion Microscopes.
- Studies on sample stress in early '70's, (Birdseye and Smith).



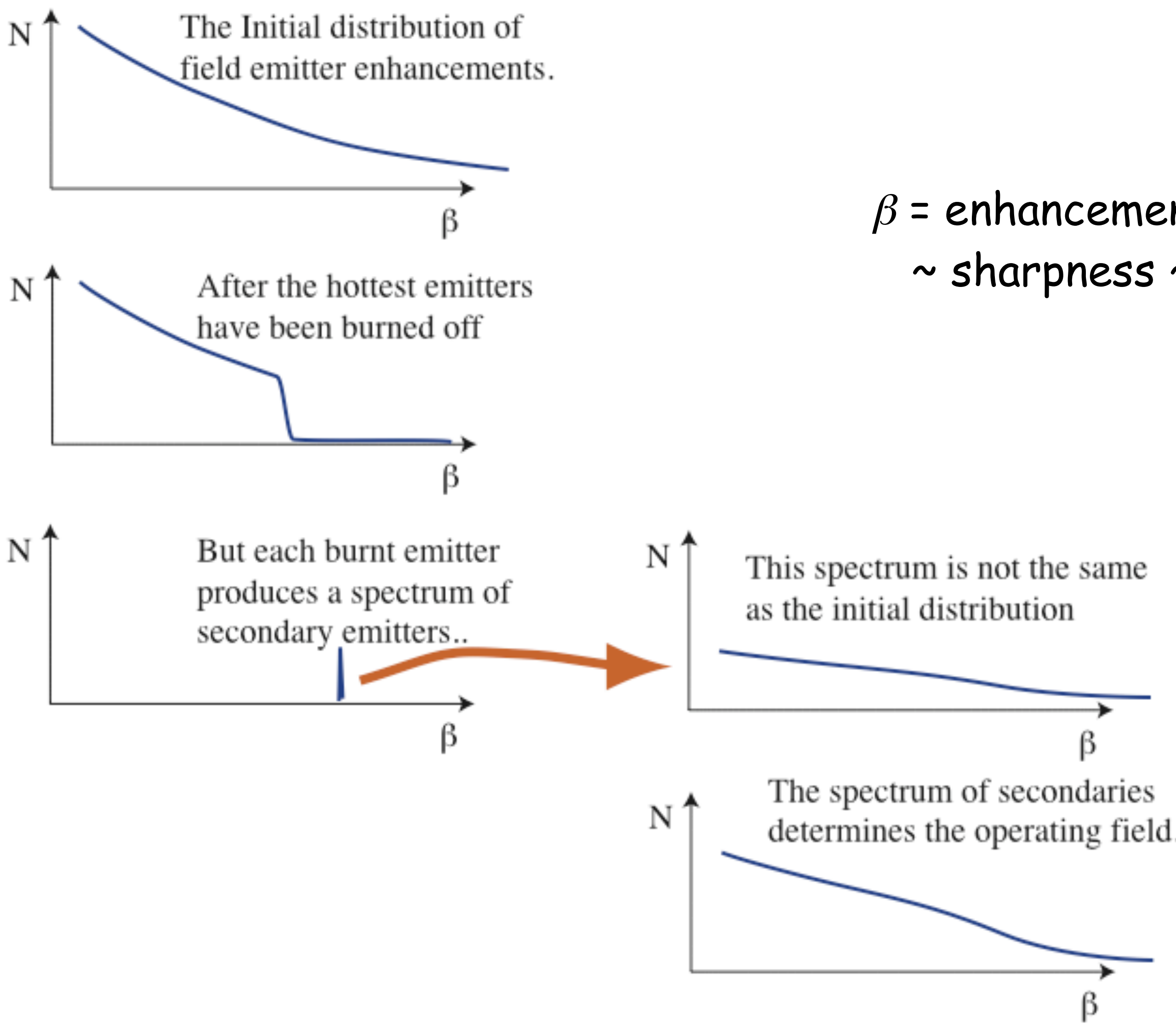
(a)

(b)

- We can see the surface under field emission conditions.

Secondary emitters.

- Secondary emitters are produced in breakdown events. We see them.

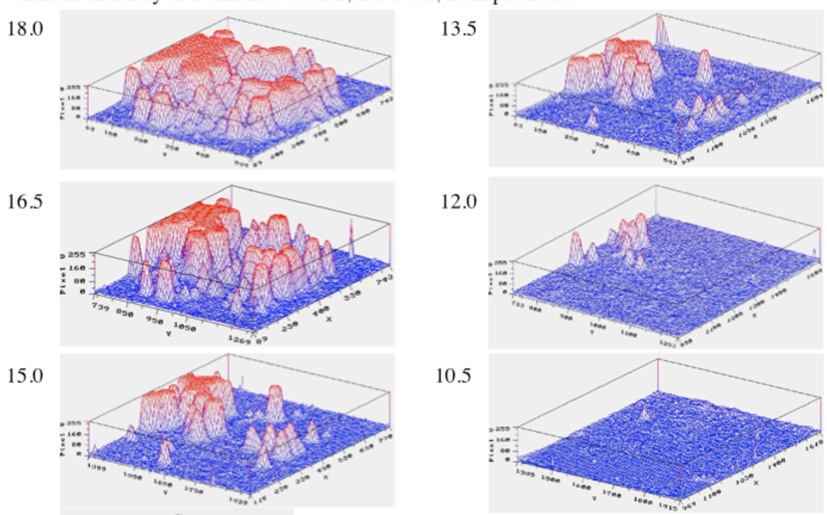


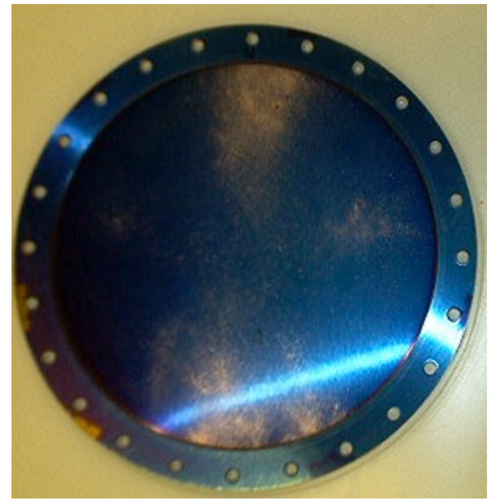
β = enhancement factor
~ sharpness ~ bump height

The secondary emitter spectrum – first measurements.

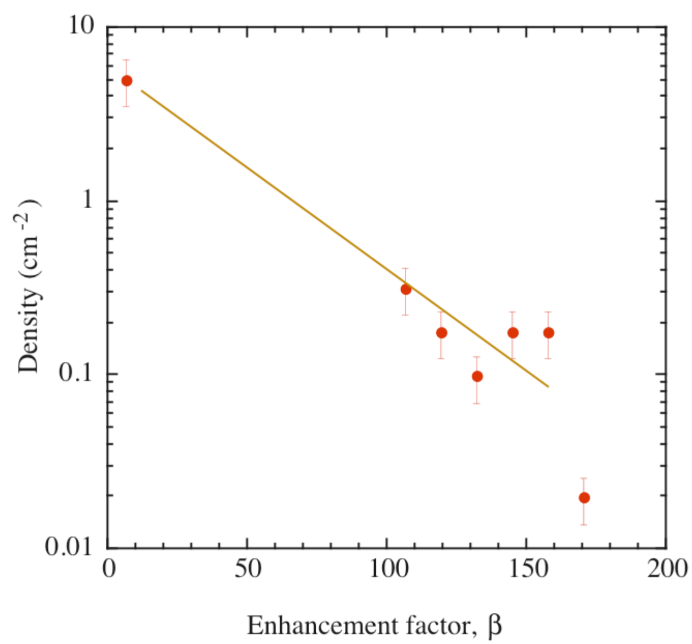
- Sources on an undamaged Be surface at different fields. . . .

- Emitter intensity as a function of field, in MV/m, from polaroids.



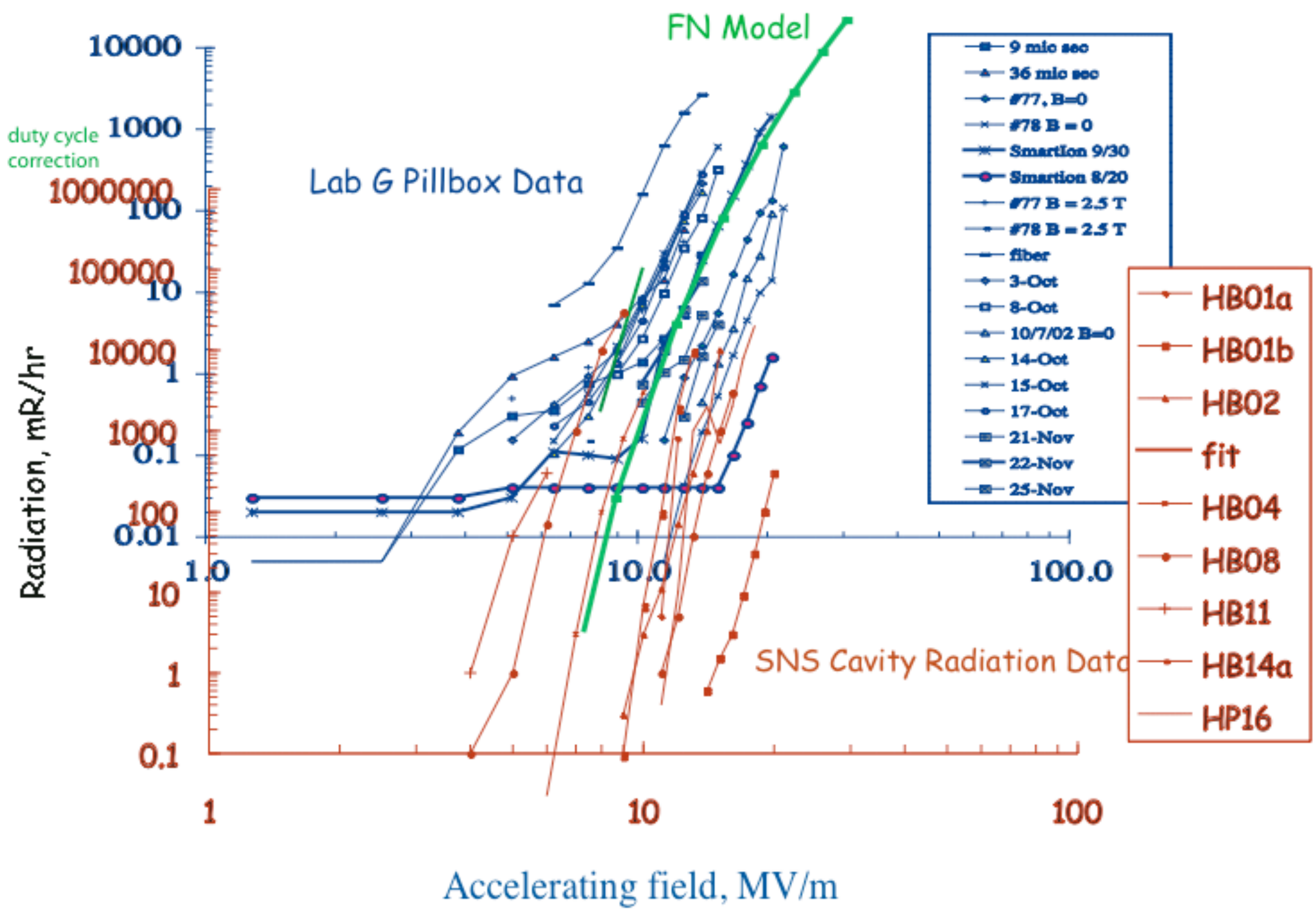


- . . . give a preliminary spectrum.



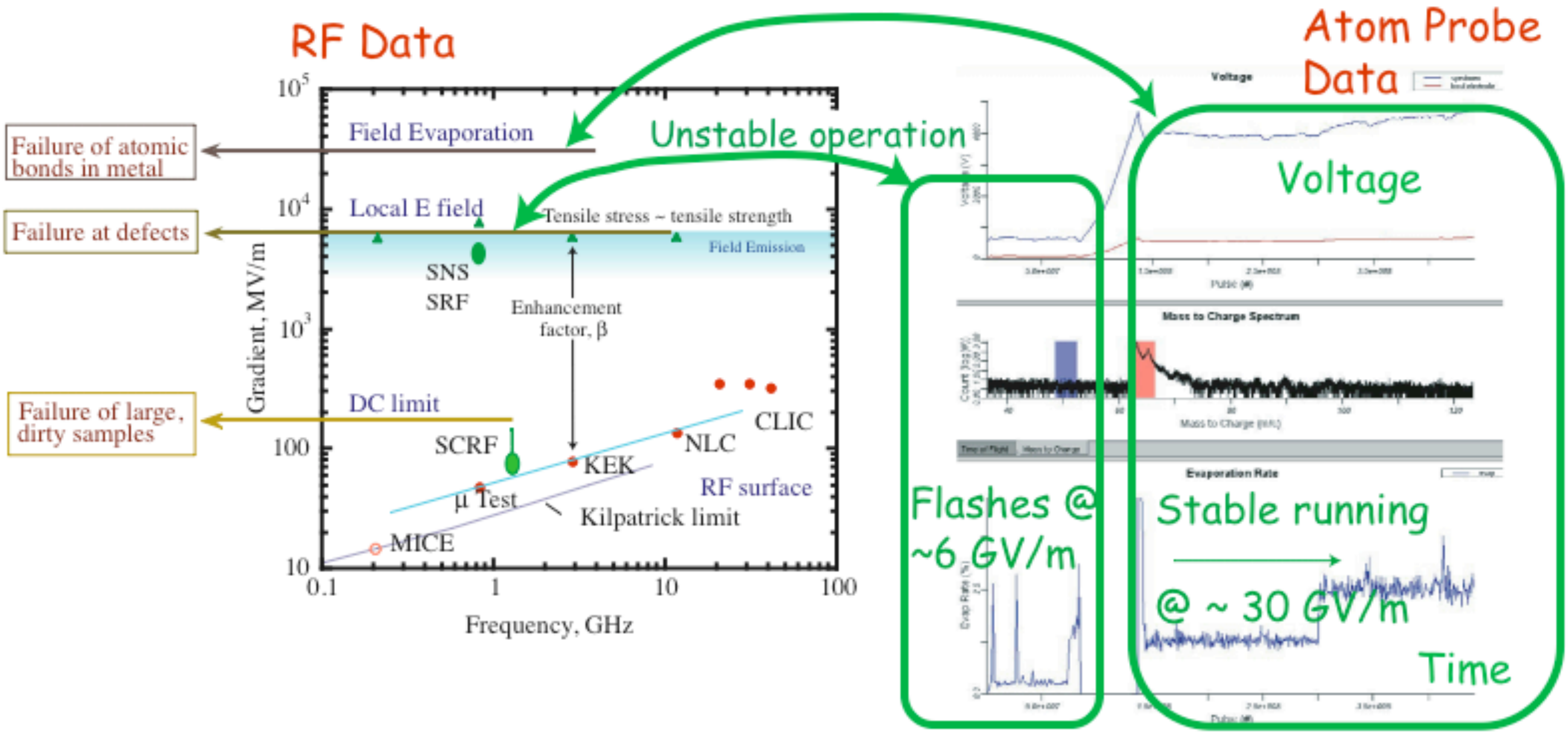
So what does all this have to do with SCRF?

- Copper systems and Superconducting systems have somewhat different limits.
- The dark currents from Cu and SC cavities can be similar.



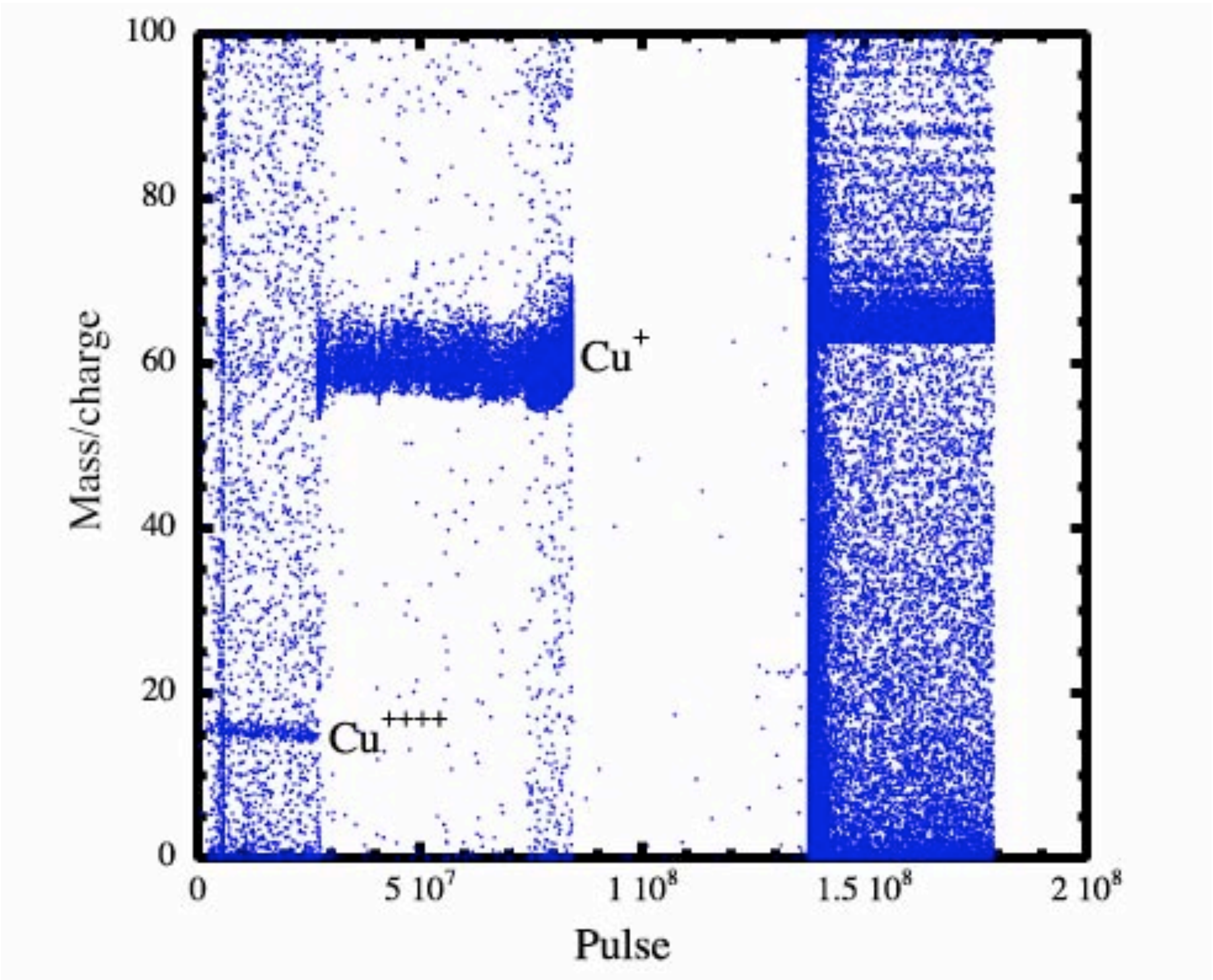
"rf breakdown triggers" are seen with Atom Probe Tomography

- LEAP data correlates with rf data. LEAP turn-on is unstable.
- Problems occur at about the right fields. (Oxide layers ?)



Surface fields can be much higher than expected.

- The "average" surface field of about 6 GV/m is, in fact about 120 GV/m.
- This can be shown by the highly ionized Cu^{++++} produced.



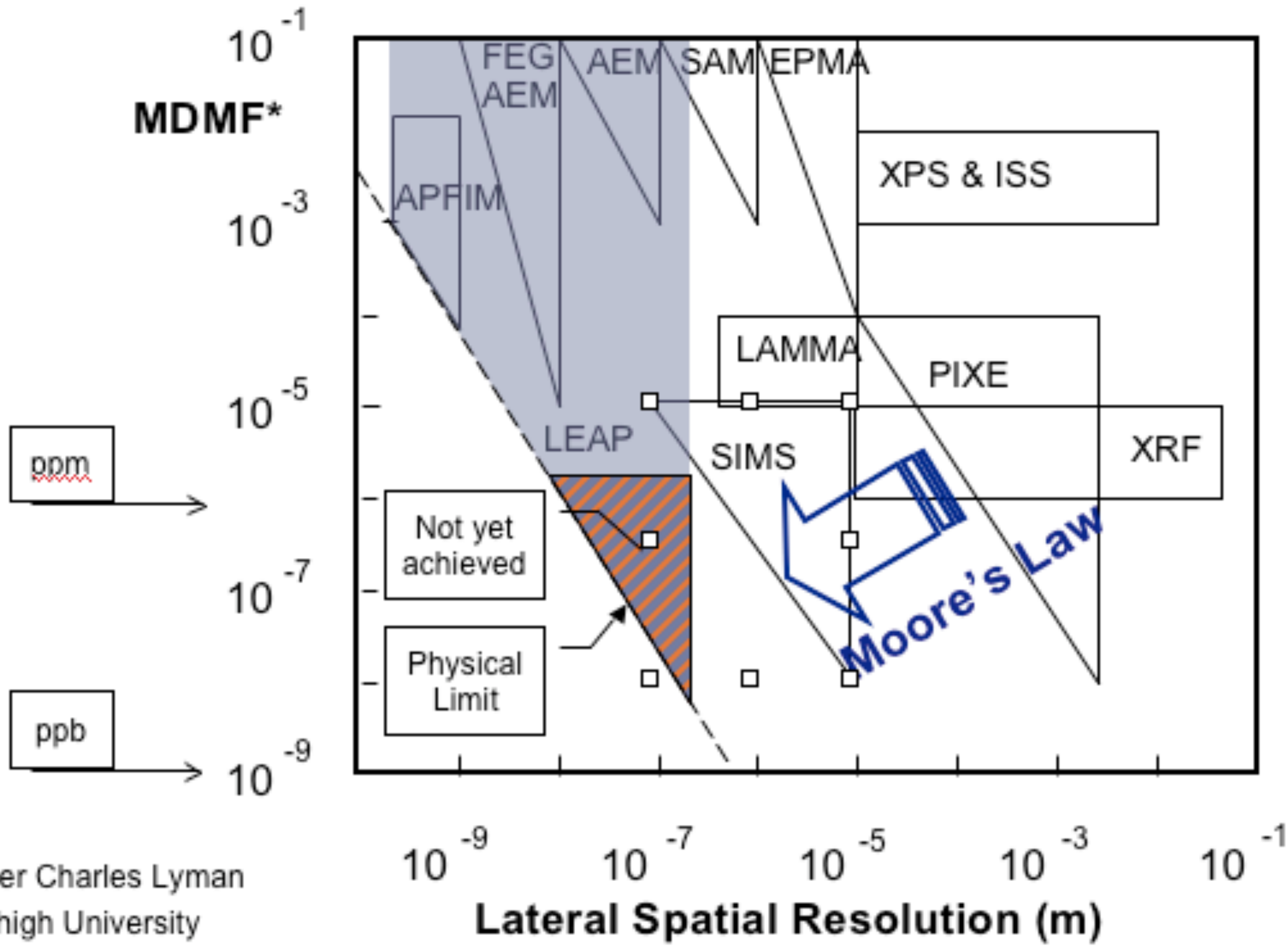
LEAP®

R&D 100

2004 Winner !

Small Times Magazine
Best of Small Tech Awards
Product of the Year 2004

The LEAP is a giant leap forward

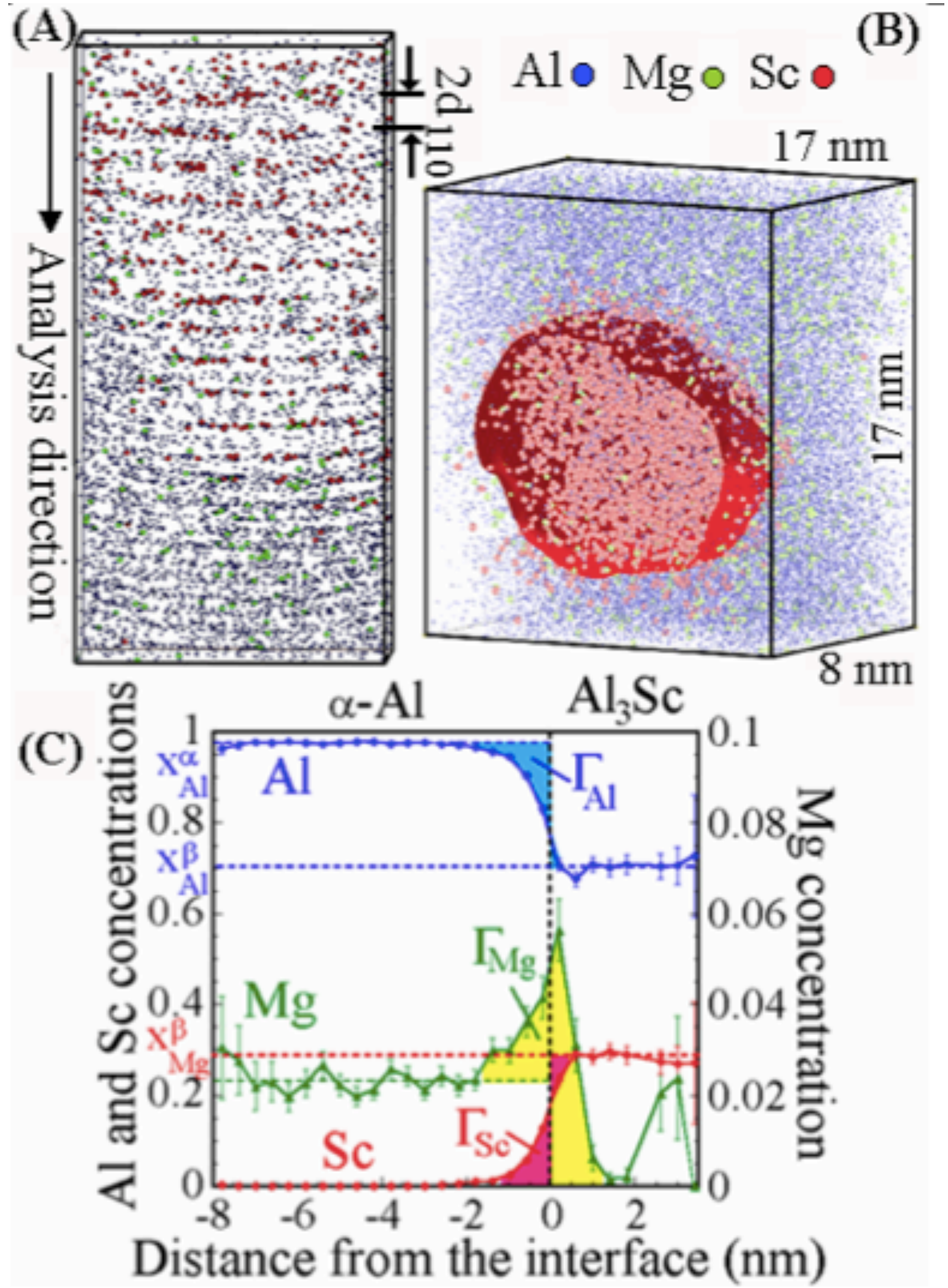


After Charles Lyman
Lehigh University

*MDMF = minimum detectable mass fraction (analytical sensitivity)

Atom Probe Data

- E. Marquis D.N.Seidman PRL 2003



(A) 3D reconstruction of an Al3Sc precipitate with a slice taken through it showing the (110) planes.

(B) 3D reconstruction of an analyzed volume from a specimen aged at 300°C for 1040 hours showing the isoconcentration surface used to delineate the Al/Al3Sc interface. Sc (Mg) atoms are in pink-red (light green), and Al is in blue.

(C) Proximity histogram showing Al, Mg, and Sc concentrations with respect to distance from the interface, which is an average for many precipitates

NUCAPT
Northwestern University
Center for Atom-Probe
Tomography

Atom Probe samples look like field emission (breakdown) sites.

- Atom Probe work is useful for two reasons:
    1) It provides a detailed look at high electric field on materials.
    2) It provides a way of looking at surface composition.

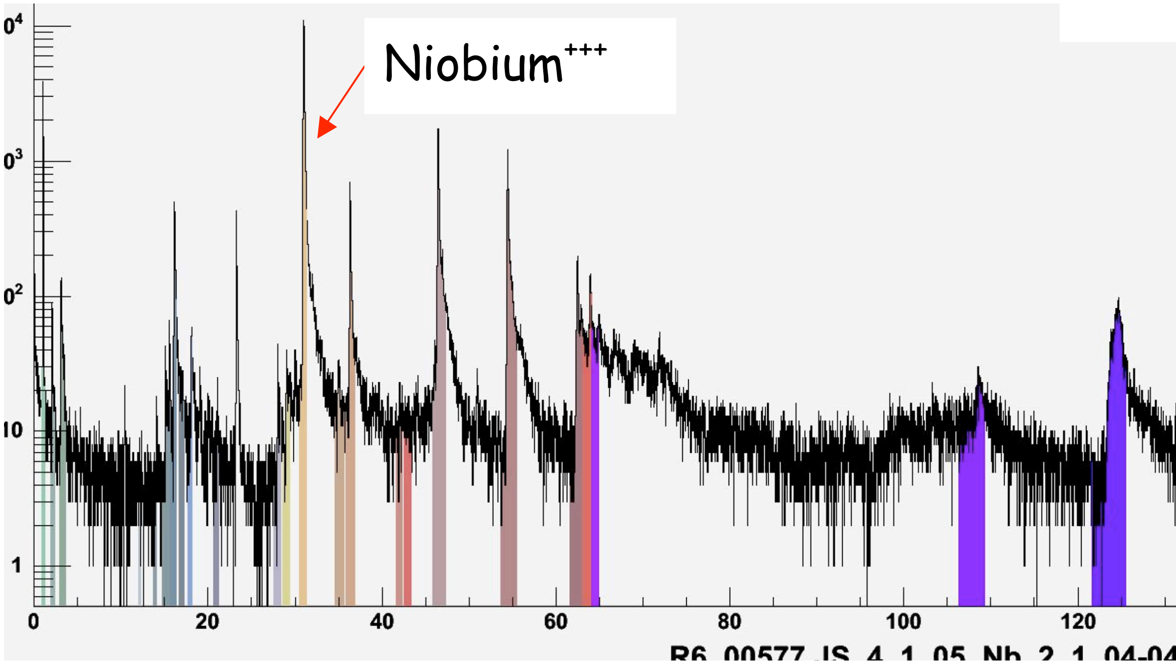
	Emitter in Cavity	Atom Probe Sample
Surface field	4 – 8 GV/m	4 – 40 GV/m
Size	~100 nm	~100 nm
Temperature	300+ K	20 – 300 K
Pulsing	200 - 12000 MHz	0.2 MHz
Stored energy	1 – 100 J	$< 10^{-6}$ J

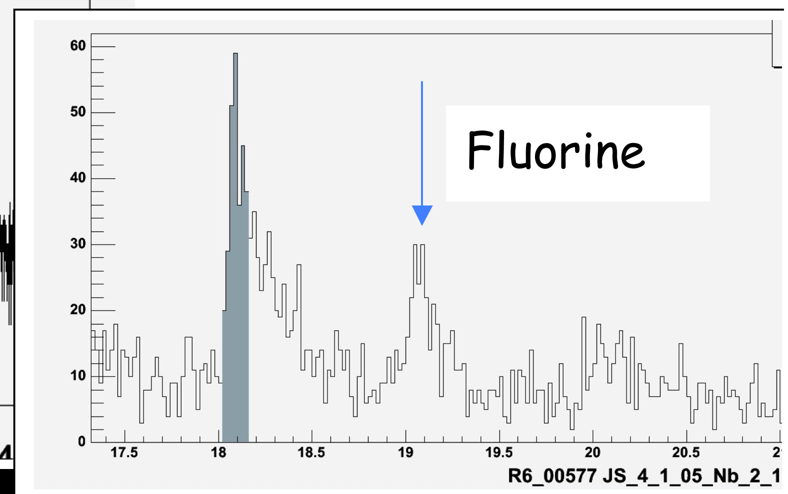
•

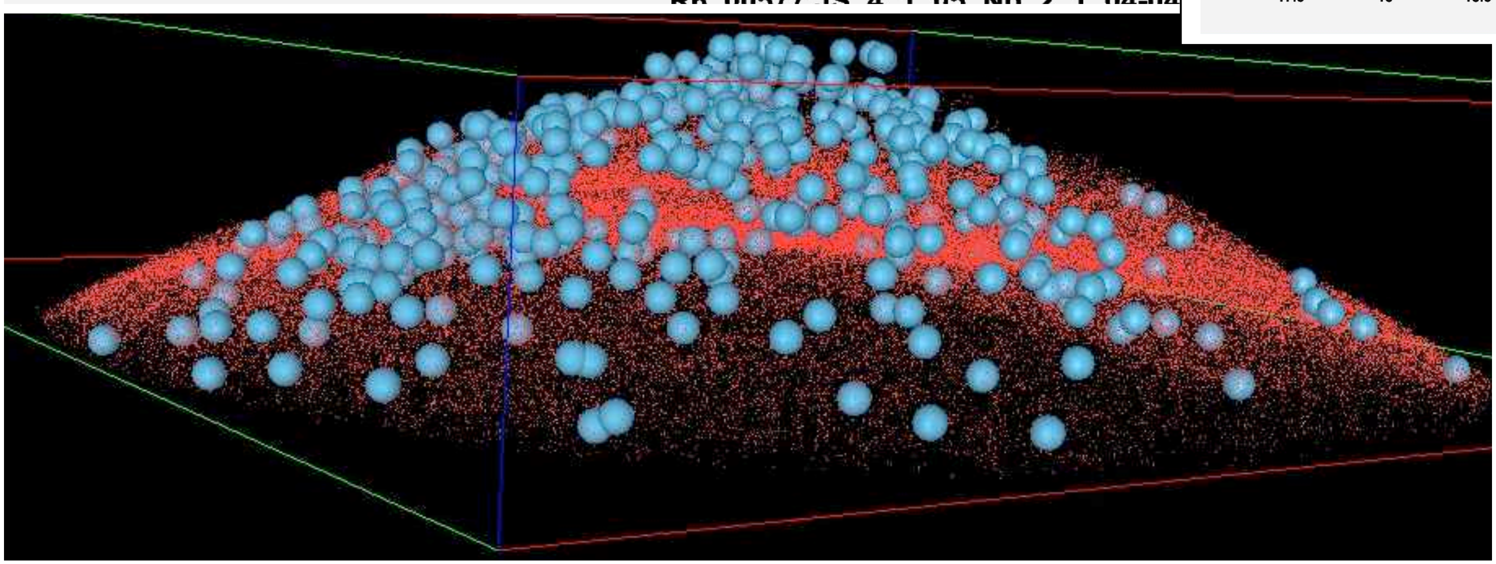
Atom Probe Data: Fluorine Contamination on Niobium

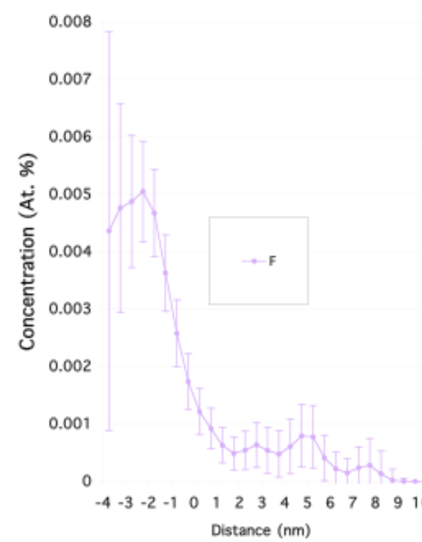
- Ions are identified by time of flight (over ~10 cm, ~1 sr).

NUCAPT
Northwestern University Center for Atom-Probe Tomography



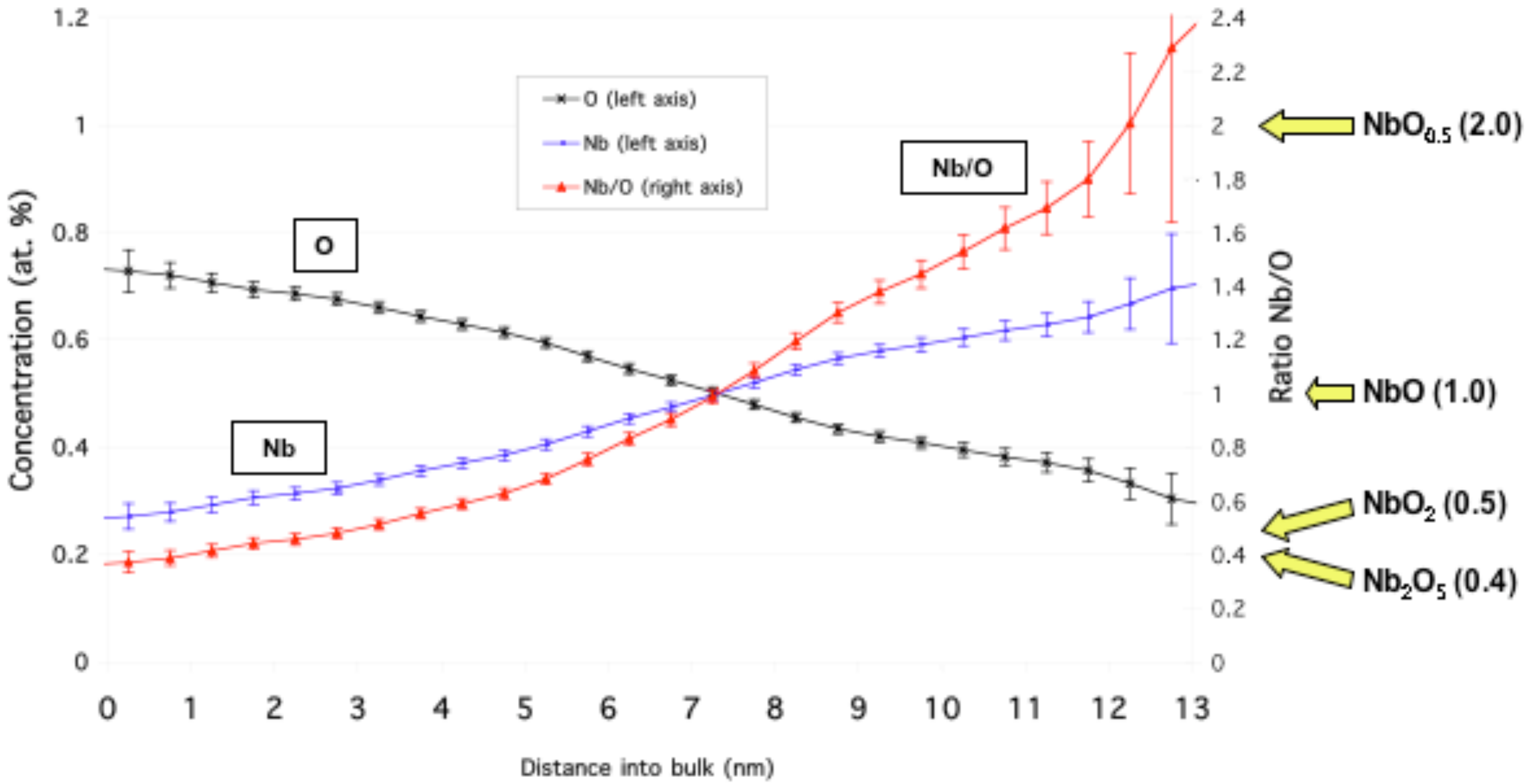






Oxide Parameters

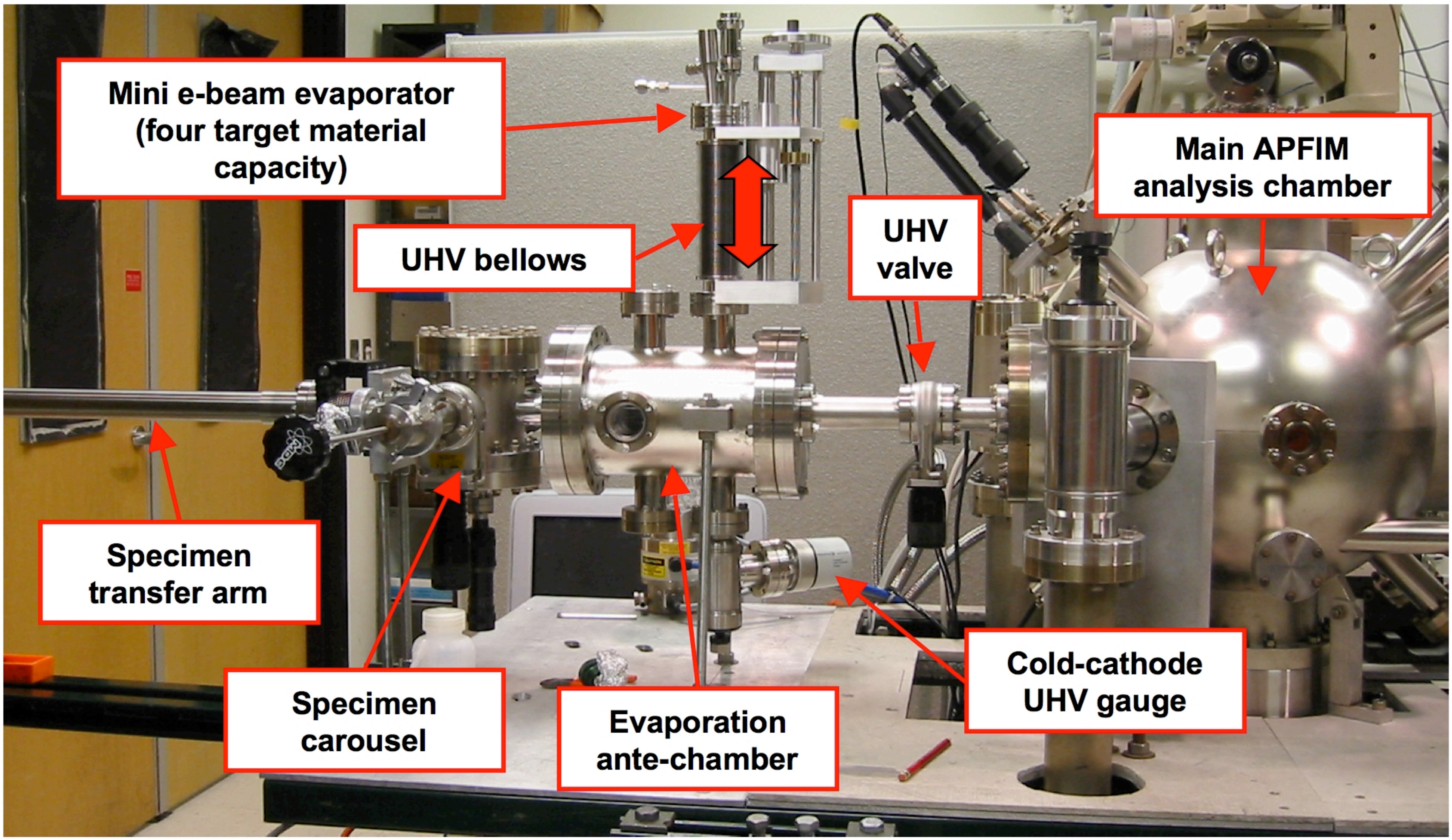
- We measure the density of different forms of the oxide with depth.



We see a clear and smooth transition from Nb_2O_5 to $NbO_{0.5}$ (= Nb_2O)

A facility to test coatings with APT is operational.

- Coatings can reduce dark currents, x rays and losses.
- It is useless to study coatings without looking at how the coating is bound.



Conclusions

- Though based on working prototypes, the last three energy frontier machines had problems.
  - ISABELLE – magnet design
  - SSC – magnet design
  - NLC – cavity design

- Superconducting rf is not a proven technology for 10 B$ machines.

- The ILC assumes areas of $\sim 10^4$ m^2 operating at ~100 MV/m for ~30 years.

- The basic physical mechanisms at work at high fields are not well understood.

- Efficient mass production assumes starting with an optimized design.

- Basic materials R&D is important.